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# TELECONNECTION IN THE MARTIAN ATMOSPHERE DURING THE 2001 PLANET-ENCIRCLING DUST STORM. L. Montabone<sup>1,2</sup>, O. Martinez-Alvarado<sup>3</sup>, S. R. Lewis<sup>2</sup>, P. L. Read<sup>4</sup>, R. J. Wilson<sup>5</sup>.

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**Introduction:** In July 2001 (Martian year 25), Mars was enshrouded by a thick veil of dust which lasted for several months and obscured the observation of its surface to spacecraft cameras and ground-based telescopes. The emergence and rapid evolution (within a few days) of multiple, isolated, regional dust storms which eventually attained planetary scale extent were observed by NASA's Mars Global Surveyor (MGS) spacecraft using high resolution camera images and the thermal profiles and dust opacity measurements provided by the Thermal Emission Spectrometer (TES) [1, 2].

We have applied a technique used in Terrestrial meteorology (sequential data assimilation, [3]) to obtain a complete, four-dimensional evolution of all the atmospheric variables during the period of this planet-encircling dust storm, even those which were not directly observed by the MGS satellite, such as surface pressure and winds. We assimilated TES nadir-pointing thermal profiles and total dust opacities in a global circulation model of the Martian atmosphere, developed jointly by the University of Oxford and the Open University in the United Kingdom, with the collaboration of the Laboratoire de Météorologie Dynamique in Paris (UK-MGCM) [4, 5, 6].

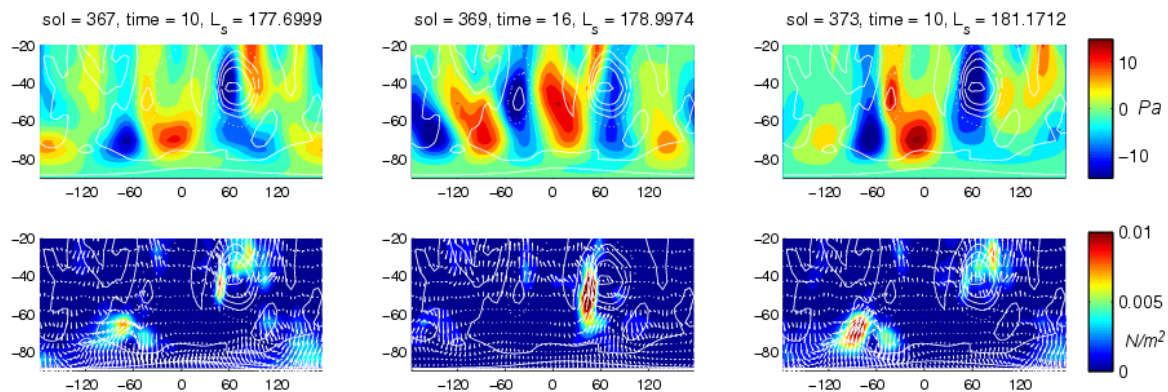
**Key events in the 2001 dust storm:** The 2001 planet-encircling dust storm was the combination of a series of subsequent regional storms which contributed to create a diffuse and global dust haze lasting for several sols [1].

The comprehension of such a global event requires

the study of several associated meteorological phenomena operating at different scales, one of which is the focus of the present paper.

The key events which characterized the evolution of the storm are the following.

- $L_S \sim 174^\circ \rightarrow 184^\circ$ : initial pulses of dust occurred along the edge of the retreating south polar cap and inside the Hellas basin. These pulses were most likely associated with transient baroclinic waves, as TES temperature observations and GCM simulations performed using the GFDL model show [7]. Results from the UK-MGCM assimilation are consistent with the hypothesis of transient waves, and show that pulses of strong near-surface ( $\sim 5$ m) wind stress are associated with the passage of low pressure systems (see Figure 1).
- $L_S \sim 185^\circ$ : the dust accumulated in Hellas moved northeastward, and settled over a region including Tyrrhena Terra and Hesperia Planum.
- $L_S \sim 186^\circ$ : the slope winds on the rims of Hellas and Isidis Planitia were reinforced as a consequence of the temperature gradients induced by the dust cloud. Enhanced near-surface wind stress and updrafts occurred in the area, leading towards the explosive behavior of the storm, as shown by LMD Mesoscale Model simulations [8].



**Figure 1:** Southern hemisphere maps of the transient component of surface pressure (upper panels) at three early times during the 2001 dust storm, and corresponding near-surface ( $\sim 5$ m) wind stress (lower panels).

- $L_S \sim 190^\circ$ : a new lifting center became active south-east of Arsia Mons, towards Syria Planum, followed by several others in the region. This will then become the main source of atmospheric dust well beyond the peak of the storm, which is reached at  $L_S \sim 212^\circ$ .

In this paper, we report on the synoptic scale meteorological phenomena associated with the evolution of the first regional dust storm around Hellas which combined with the secondary lifting centers in the Tharsis region to attain a planetary extent. We highlight the dynamical events that connected distant favourable dust lifting regions and activated the secondary lifting centers thousands of kilometres apart.

**Results from data assimilation:** These long-distance effects (teleconnections) are due to the interaction between localised atmospheric heating, produced by dust particles aloft through the absorption of incident visible radiation, and the atmospheric thermal tides.

In particular, the components of the thermal tide which are affected most by the presence of dust in the Martian atmosphere are the following (see also [9, 10]).

- The diurnal mode (zonal wavenumber 1, period of 1 sol, westward propagating wave).
- The semidiurnal mode (zonal wavenumber 2, period of 1/2 sol, westward propagating wave);
- An equatorially-confined, eastward propagating, free mode with zonal wavenumber 1 and period of approximately 1 sol (that may resonate with the interaction between the diurnal component and the Martian zonal wavenumber 2 topography), equivalent to an equatorial Kelvin mode.

On Mars, the phase difference between the diurnal component ( $S_1$ ) and the diurnal Kelvin mode (DK1) on short time scales (few sols) is usually constant, but at the time of the onset of the 2001 dust storm this phase difference changed dramatically (by almost  $180^\circ$ ) during an interval of only five sols. This happened because of the localized anomalous radiative forcing produced by the first explosive burst of dust in a particularly favourable location near the Equator, at about  $20^\circ\text{S}$  in Hesperia Planum, north-east of the Hellas basin ( $L_S \sim 186^\circ$ ).

This “phase slip” is well observed in the signal of surface pressure (Figure 2), and has an important consequence: the minima of low pressure, which are generated by the constructive interference among the main components of the tide and which are usually located at fixed longitudes on short time scales (stationary wavenumber 2 wave), drifted eastwards and one of

them settled over the Tharsis region. A synoptic scale surface pressure anomaly can produce a local effect on the winds, and the particularly favourable orography of the Tharsis region allowed a strengthening of the local slope winds. The increased local wind-stress (see Figure 3), associated with topographically-enhanced convergence of air masses and vertical updrafts, created the conditions for the onset of a secondary dust lifting center around Arsia Mons ( $L_S \sim 190^\circ$ ). This secondary storm soon merged with the first regional dust storm originated thousands of kilometres apart around the Hellas basin, and helped the 2001 dust storm to spread globally.

**Results from control simulation:** The results from the assimilation of TES observations into the UK-MGCM highlight the teleconnection between Hesperia Planum and the Tharsis region during the 2001 dust storm, when an anomalous radiative forcing is introduced by the regional dust storm developing north-east of Hellas.

In order to verify the dynamically active nature of such a teleconnection and to quantify its relative impact in a controlled experiment, independently from observations, we carried out a numerical simulation using the UK-MGCM in free-running mode, without assimilation. The anomalous radiative forcing was introduced using a Gaussian distribution of total dust optical depth with time-dependent amplitudes and variances modeled on the basis of the TES-observed dust optical depth in Hesperia Planum around  $L_S \sim 186^\circ$ . Furthermore, we also carried out the same numerical experiment with an independent model (the GFDL Martian GCM) in order to ensure that this effect was model-independent.

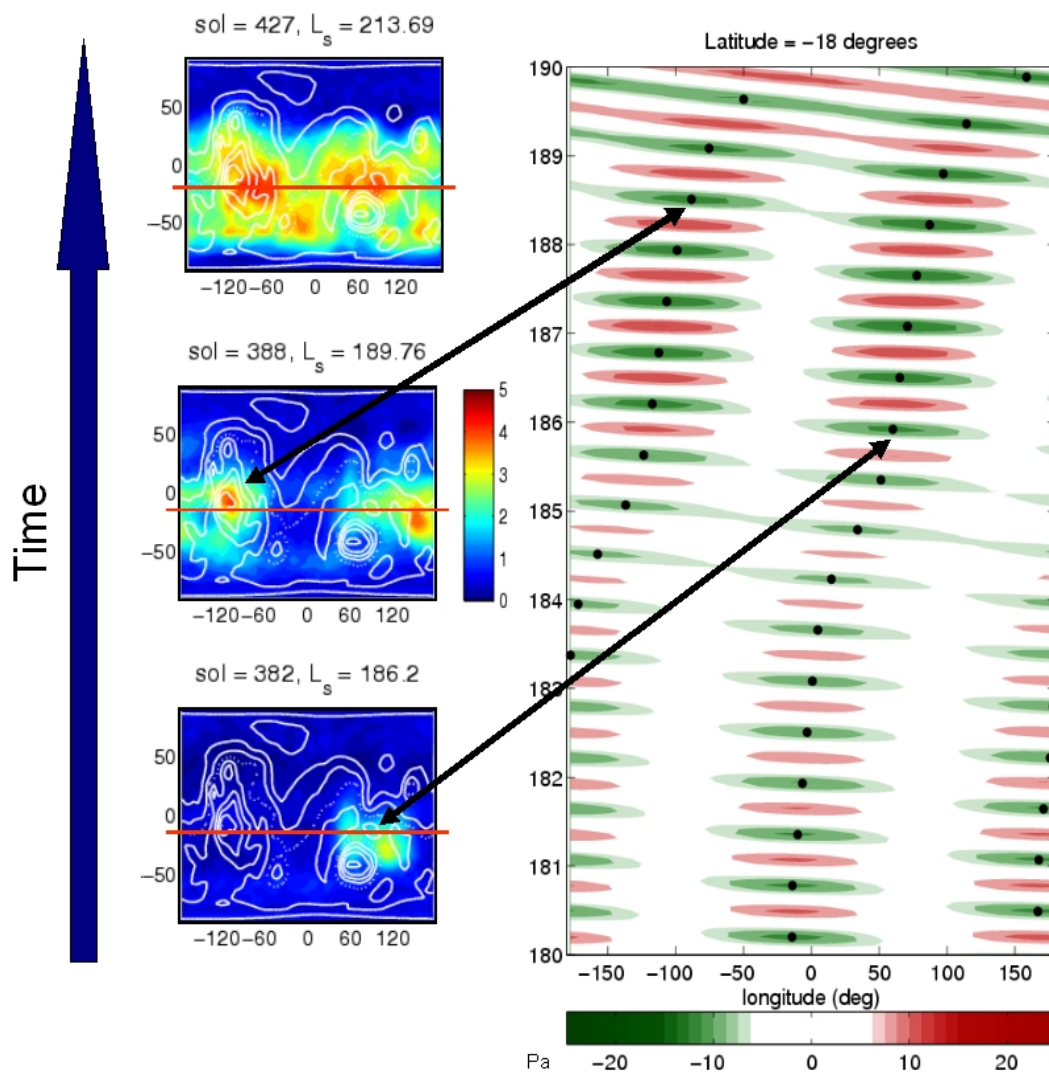
Figure 4 shows the results obtained with the UK-MGCM, the results obtained with the GFDL-MGCM being substantially the same. The local radiative forcing centered at  $90^\circ\text{E}$ ,  $18^\circ\text{S}$  in Hesperia Planum produces the drifting of the low pressure minima even in the control simulation, whereas no drifting is observed when a constant value of dust optical depth is used everywhere on the planet (not shown here).

**Conclusions and future work:** We have studied the meteorological phenomena which characterized the development of the 2001 dust storm on Mars at  $L_S \sim 186^\circ$  and caused it to attain the planetary scale.

We found a long-distance radiative-dynamical coupling (or teleconnection) between the site where the storm originally had its explosive growth (Hesperia Planum) and the area where subsequent regional storms appeared (Tharsis region). We identified the origin of such a teleconnection as being associated with a zonal phase slip between the diurnal component and the diurnally resonant Kelvin wave component (1-

sol period, zonal wavenumber-1 wave propagating eastwards) of the thermal tides. This phase slip could be produced when an anomalous heating in the lower atmosphere at equatorial latitudes creates a longitudinal shift in the forcing, usually dominated by the

wave-2 component of the topographic forcing. During the 2001 dust storm, this anomalous event occurred at  $L_S \sim 186^\circ$  when the intense regional dust storm in Hesperia Planum had its peak.



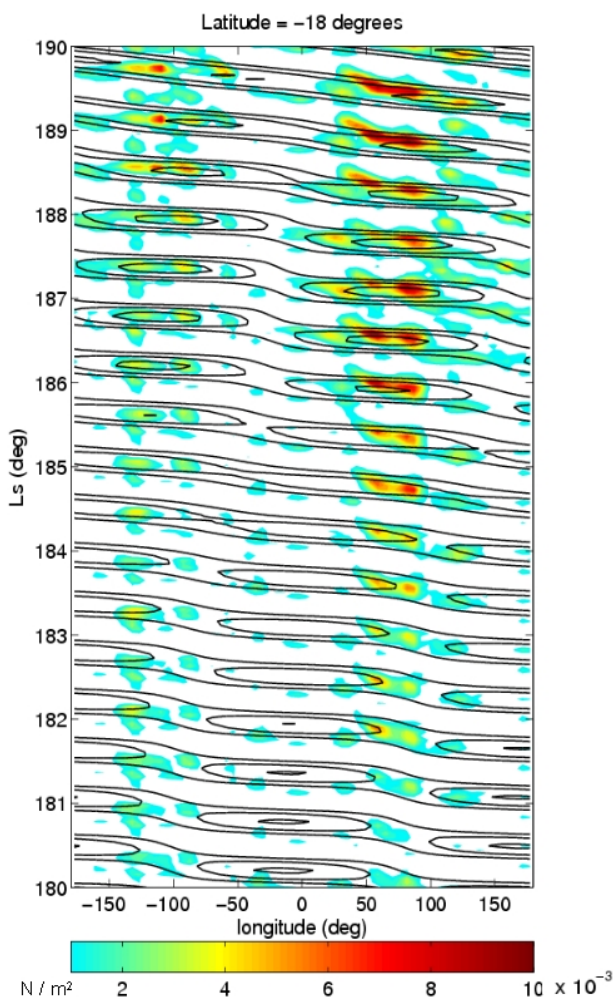
**Figure 2:** The left panels show maps of total (equivalent visible) dust opacity at a reference pressure of 610 Pa for three key times during the evolution of the 2001 dust storm. Topographic contours are superimposed. The red lines correspond to latitude =  $18^\circ\text{S}$  at which the longitude-time plots are provided. The right Hovmöller plot shows the time evolution of the longitudinal anomalies of surface pressure with respect to the trend average at the given latitude. Only the diurnal component of the thermal tide (wavenumber-1, 1-sol period, and propagating westwards) and the non-migrating tide equivalent to a near-resonant Kelvin wave (wavenumber-1, 1-sol period, and propagating eastwards) are included. The black dots mark the minima of the negative pressure anomalies.

Future work will address a detailed study of the mechanisms connecting the synoptic scale and the mesoscale during the 2001 dust storm event, in order to fully characterize the effects of the displacement of

the large-scale low pressure systems on the local winds and the dust lifting.

Analysis of other dust storms is also ongoing, including the regional dust storm during MY 26 at  $L_S$

$\sim 210^\circ$ , and the recent dust storm in MY 28 (July 2007) which encircled the southern hemisphere. In particular, it is important to understand the reasons why the regional storm in MY26, which was reinforced in the plains between Isidis Planitia and the Hellas basin at equatorial latitudes, did not lead to any sustained teleconnection but faded away in just a few sols.

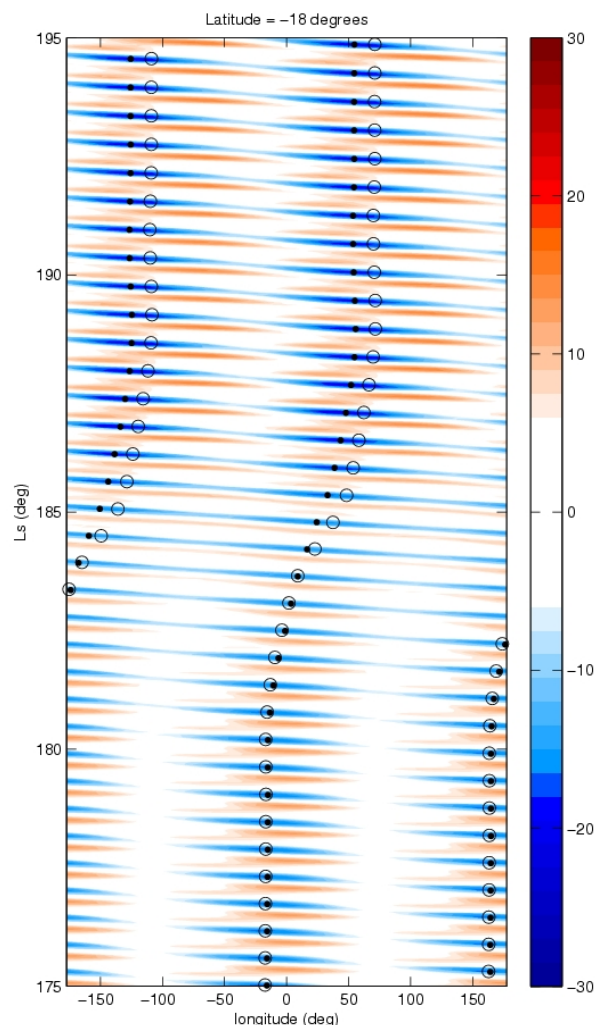


**Figure 3:** Hovmoller plot showing the time evolution of the near-surface wind stress at lat=18°S (colors) and of the negative anomalies of surface pressure as in Figure 2 (contours, separated by 5 Pa)

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Abstract in this volume. [9] Lewis, S. R., and Barker P. R. (2005) *Adv. Space Res.*, 36, 2162–2168. [10] Wilson R. J. et al. (2008) Abstract in this volume.



**Figure 4:** Time evolution of the longitudinal anomalies of surface pressure (diurnal + Kelvin components) at lat=18°S for the control simulation. We impose an anomalous radiative forcing modeled using a Gaussian distribution of total dust optical depth which is centered at 90°E, 18°S. The amplitude of the distribution is non-zero starting from  $L_S \sim 182^\circ$ , and varies according to the peak values of DOD measured by TES in that area at that time. The black circles mark the minima of the diurnal+Kelvin components of the negative surface pressure, whereas the dots mark the minima in the case one includes the diurnal, semidiurnal and Kelvin components, together with other components with minor amplitudes emerging from the interaction between the diurnal component and the wave-2 topography.